NUMERICAL STUDY ON THE EFFECT OF DIESEL ENGINE EMISSIONS BY CONTROLLING WATER INJECTION THROUGH THE EXHAUST MANIFOLD

SHESHANTH BONTHI¹ & D. SENTHIL KUMAR^{2*}

¹PG Student, Department of Mechanical Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, India

²Assistant Professor, Department of Mechanical Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, India

ABSTRACT

NO_x and soot emissions have become an important concern for diesel engine due to the stringent emission standards and also due to the trade-off characteristics between them. Water injection is one of the efficient methods to reduce NO_x and soot emissions with better trade-off. A computational study is conducted to investigate the NO_x and soot emissions when water is injected through exhaust manifold in a single-cylinder DI diesel engine. The simulations are conducted for two cases: i.) Water injection in the exhaust manifold when the exhaust valve is open ii.) Water injection in the exhaust manifold when the exhaust valve is reopened during suction stroke. These simulations are carried out for three water injection quantities 6mg, 16mg and 24mg. The water injection could reduce NO_x emissions with better NO_x and soot trade-off, due to the thermal, dilution and chemical effects. The water injection through exhaust manifold strategy utilizes the exhaust gas heat to vaporize the water molecules and also creates an internal EGR effect. Results indicated that the NO_x is reduced by about 73-75% when 16mg of water is injected. At this water quantity, it is also observed that the NO_x and soot trade-off is less. In addition, as the water quantity increases the difference in NO_x and soot emission values of the two cases are getting narrowed.

KEYWORDS: Diesel Engine, Water Injection, Exhaust Manifold, NO_x Reduction, CFD

Received: Jun 10, 2020; **Accepted:** Jun 30, 2020; **Published:** Aug 01, 2020; **Paper Id.:** IJMPERDJUN2020562

1. INTRODUCTION

Engines are the energy generating source for most of the automobiles and many industrial applications. Engines use fossil fuel as the working fluid, which makes them to be the major concern for environmental pollution. Due to the increase in vehicle population, the emission has become a severe problem. Reduction of engine emissions has become the reason for the implementation of the emission standards. Many kinds of researches are going on for the reduction of engine emissions. Among diesel engine emissions, NO_x and soot emissions are more concerned than HC and CO emissions, since HC and CO emissions are very less compared to NO_x and soot. NO_x formation mechanism is based on the Zeldovich equations [1]. The rise in the cylinder pressure leads to high temperature in the combustion process, at these high temperatures, diatomic nitrogen molecules break into monatomic nitrogen molecule and then oxidises to form NO. The NO generated in the post flame gases are more than NO generated at the flame front. The NO_x and soot emissions have a trade-off with each other which makes it hard to reduce both of them simultaneously. Soot is the carbonaceous matter that is formed due to unburnt hydrocarbons and some lubricant oil traces. For NO_x and soot reduction there are many strategies like altering fuel injection, changing

compression ratio, exhaust gas recirculation, water introduction into the combustion chamber, after treatment systems etc.

Water introduction is one the strategy which reduces the NO_x and soot emissions with less trade-off difference. When water is introduced into the cylinder it creates three effects thermal, dilution and chemical effects on the combustion which contributes to NO_x and soot reduction. The thermal effect leads to the absorption of latent heat present in the chamber by the water molecules, this tends to the decreased flame temperature which helps in reducing the NO_x emissions [2][9]. In dilution effect, due to the presence of water molecules in a combustion mixture will decrease the availability of oxygen, which leads to increase in mixing rate of fuel and air, thus the mass fraction of fuel that burns under premixed condition also increases [3][9][10]. This leads to less NO_x and soot formation. In chemical effect, the water introduction into the cylinder leads to the increase in OH radicals, which effects the soot oxidation and reduce the soot formation [3][4].

Water introduction into the cylinder can be done in three ways water-diesel emulsion, direct water injection and water injection through the manifold. Water-diesel emulsion generally composes of diesel, water and an emulsifier which is injected as the fuel into the cylinder. But this technique requires a separate emulsifier to blend water and diesel, which complicates in the fuel economy and performance. Direct water injection is a technique in which the water is injected from the fuel injector with two individual holes or by a separate injector for water injection. In this technique, water injection timing can be varied. But this technique leads to the design complication for engine and fuel injector. Water injection through the manifold is a better and feasible technique for water introduction into the cylinder. In this water injection through the intake manifold is a well-known strategy, in which water is injected through the intake manifold.

G. Greeves, I. M. Khan and G. Onion [3] conducted experiments on water introduction into the cylinder to observe the effect on emission and combustion of a diesel engine. The experiments were conducted on water injection in inlet manifold, direct water injection into the cylinder and water-fuel emulsion injection into cylinder. It is observed that because of water addition into the chamber, NO_x is reduced up to 70%. Besides, it can reduce CO and smoke up to 50%. Masahiro Ishida, H. Ueki and D. Sakaguchi [6] examined theoretically and experimentally the NO formation when water is injected at inlet ports. The water quantities of 0.01, 0.02 and 0.03kg of water per every 1kg mass of air injected into inlet ports where analysed. A huge reduction in NO_x emission about 50% is observed when 0.03kg of water per every 1kg mass of air is injected in the ports.

Xiaokang Ma, F. Zhang, K. Han, Z. Zhu and Y. Liu [7] studied on emission and combustion effects due to water injection into the manifold. The investigation was based on CFD analysis on intake manifold water injection. The study concludes that water injection reduces the in-cylinder mean pressure and temperature, which leads to longer ignition delay. This further tends to a huge decrease in NO_x and Soot emissions. It is also observed that when compared to the thermal effect, dilution effect and chemical effect, the dilution effect caused by water injection in intake manifold plays an important role in engine combustion and emissions. F. Bedford, C. Rutland, P. Dittrich, A. Raab and F. Wirbeleit [2] conducted CFD analysis on direct water injection to observe the emission and combustion parameters. The water injection was modelled with advancing the injection timing. It is observed that there is a significant decrease in NO_x , particulate matter and specific fuel consumption. It is also observed that more the water injection can increase the injected liquid volume up to the point where the injection duration is long. This leads to an increase in soot emissions.

M. Nour, H. Kosaka, A. K. Abdel-Rahman and M. Bady [5] conducted experiments on water injection through the exhaust manifold. The emission and combustion effects due to the water injection quantities of 6, 12, 24 and 40 mg/cycle in the exhaust manifold was observed and compared with the effects due to EGR. It was observed that the water injection

can increase the indicated mean effective pressure up to 11%, reduction NO_x up to 45% and decrease in soot when compared to EGR. It is also observed that the combined EGR and water injection strategy could reduce the NO_x and PM trade-off. M. Farag, H. Kosaka, M. Bady and A. K. Abdel-Rahman [8] experimented on intake manifold water injection and exhaust manifold water injection with 40 mg/cycle water quantity. The emission and combustion parameters were compared in both cases and observed that the intake manifold water injection reduces NO_x emissions up to 88%, whereas the exhaust manifold water injection improves engine performance while reducing NO_x and soot emissions.

From these researches, it can be observed that water injection will reduce NO_x and soot emissions. In addition, when utilized with EGR there is a slight reduction in the performance. This could be overcome by using water injection through the exhaust manifold. This technique also helps to recover the exhaust waste heat. The present work is based on the water injection through exhaust manifold by water injection when the exhaust valve is opened and water injection when the exhaust valve is reopened in suction stroke. This technique utilizes exhaust gas heat to vaporize the water molecules. Due to the exhaust valve is open, the injected water enters into the cylinder with some amount of exhaust gas. This gives the additional benefit of the internal Exhaust Gas Recirculation (EGR). The main objective of this work is to reduce the NO_x emission with less NO_x and soot trade-off using water injection through the exhaust manifold. The present work is concentrated on the computational study of the NO_x and soot behaviour when water is injected through the exhaust manifold.

2. METHODOLOGY

Figure 1: Schematic Diagram of the Setup

Figure 2: Engine Geometry

Simulations are conducted on a four-stroke single-cylinder direct injection CI engine, with the engine specifications as shown in tables 1 to 3. The schematic diagram for the simulation of water injection through exhaust manifold setup is shown in figure 1. The geometry of the engine is modelled in SolidWorks designing software, as shown in figure 2. Meshing and Simulations are carried out in ANSYS. For this simulation, the ANSYS IC Engine (Fluent) is utilized, since this module can generate the dynamic simulation by using the inbuilt solver algorithm. The model used for the simulation is a standard k-epsilon model with NO_x and soot enabled. The soot model used is Moss-Brookes model. The simulation is run with engine speed 1800 rpm, 2.45 bar and 333K initial conditions. The surface temperature of the piston, cylinder head and cylinder walls are estimated to be 560K, 480K and 440K respectively as boundary conditions.

Table 1: Engine Specification

Parameter	Specification
Bore	89mm
Stroke	100mm
Displacement	622 cc
Compression ratio	15:1
Engine Type	4 stroke single cylinder CI engine
Fuel	Diesel
Crank Radius	45mm
Connecting Rod Length	144.3mm

Table 2: Valve Timing

Parameter	Specification
Intake Valve - IVO, IVC	14° BTDC, 30° ABDC
Exhaust Valve – EVO, EVC	39° BBDC, 5° ATDC
Exhaust Valve ReOpening	20° ATDC
Exhaust Valve ReClosing	60° ATDC / 60°

Table 3: Fuel and Water Injection Specifications

Parameter	Specification
Fuel Injection	
Fuel Quantity	32 mg
Fuel Injection Timing	8° BTDC / 352°
Fuel Injection Duration	26° crank angle
Water Injection	
Water Injection Quantity	6 mg, 16 mg and 24 mg
Injection Timing (WI @ Exhaust Valve opened)	12° BTDC / -12°
Injection Timing (WI @ Exhaust Valve Reopened)	40° ATDC / 40°
Injection Duration	16° crank angle

3. RESULTS AND DISCUSSIONS

The simulations for the water injection through exhaust manifold are conducted with two cases i) Water injection when the exhaust valve is open and ii) Water injection when the exhaust valve is reopened in the suction stroke. The results are then compared with the normal combustion simulation results.

3.1. Water Injection when the Exhaust Valve is Open

In this case, the water is injected between the time when the exhaust valve and intake valve both are open, 12° BTDC at the suction stroke. Three simulations are conducted in this case with different water injection quantities of 6mg, 16mg and 24mg. In these three simulations, the NO_x and soot parameters are monitored and plotted in figures 3(a) and 3(b). The NO_x and soot emission behaviour can be observed through these plots.

Figure 3(a): NO_xEmission for WI@EVO

Figure 3(b): Soot Emission for WI@EVO

Due to the water injection, the NO_x is reduced by about 73% than the normal combustion. But when it comes to the soot emission a drastic increase is observed, this is due to the trade-off between NO_x and soot. When the average of these plots is taken and compared, it is observed that as the water quantity increases the NO_x values decreases, but whereas soot behaviour is not linear. This can be seen in figure 4. Among the three water quantities, 16mg of water injection has a less trade-off, since it has less soot value with almost less NO_x value. Thus, the less trade-off for the NO_x and soot emissions can be near to the 16mg of water injection in this study.

Figure 4: Average NO_x and Soot Plot for WI@EVO

3.2. Water Injection when the Exhaust Valve is Reopened

In this case, the water is injected when the exhaust valve is reopened during suction stroke. The exhaust valve is reopened, so that the water can be injected at a different timing. This strategy gives the feasibility for finding the optimal injection timing when water is injected through the exhaust manifold. But this work is only conducted on single water injection timing when the exhaust valve is reopened at 40° ATDC in suction stroke. The three simulations with 6mg, 16mg and 24mg of water injection are conducted and plotted in figures 5(a) and 5(b). The NO_x and soot behaviour are similar to the previous case but with different values.

Figure 5(a): NO_x Emission for WI@EVRO

Figure 5(b): Soot Emission for WI@EVRO

Due to the water injection, the NO_x is reduced by about 75% than the normal combustion. But when it comes to the soot emission a drastic increase is observed, this is due to the trade-off between NO_x and soot. When the average of these plots is taken and compared as shown in figure 6, it is observed that as the water quantity increases the NO_x values decreases, but whereas soot behaviour is not linear. Among the three water quantities, 16mg of water injection has a less trade-off, since it has less soot value with almost less NO_x value. Thus, the less trade-off for the NO_x and soot emissions can be near to the 16mg of water injection in this study. This case also has the same behaviour as the previous one, but the difference in these cases can be seen when they are compared with each other.

Figure 6: Average NO_x and Soot Plot for WI@EVRO

Figure 7 is plotted with average values of the NO_x and soot values from both the cases to observe the difference when the water injection timing is changed. As both cases have similar behaviour with a slight value difference. But the difference in these values is getting narrowed when the water injection quantity is increased. From the comparison of these cases, it is observed that the water injection through the exhaust manifold can reduce the NO_x emissions about 73-75% with less trade-off difference when water injection quantity is near 16mg. From the comparison plot, it is also observed that the optimal water quantity can be near to the greater than or equal to 16mg since the behaviour is much similar.

Figure 7: Comparison of Both Cases

4. CONCLUSIONS

A computation study is conducted to investigate the NO_x and soot behaviour when the water is injected through the exhaust manifold in a diesel engine. The simulations are conducted by considering the two cases of water injection when the exhaust valve is open and the exhaust valve is reopened with 6mg, 16mg and 24mg water injection quantities. From the simulation results of these two cases, it is observed that,

- NO_x can be reduced by about 73-75% with less trade-off difference in the exhaust manifold water injection.
- 16mg of water injection quantity has the optimal NO_x and soot emissions behaviour.
- As the water injection quantity increases the emission value difference between both cases comes closer.
- From this study 16mg of water injection is observed to be the optimal water quantity, but this cannot be assured until the technique is studied on other emission and performance characteristics.

REFERENCES

1. Zeldovich, Y. A., D. Frank-Kamenetskii, and P. Sadovnikov. "Oxidation of nitrogen in combustion." Publishing House of the Acad of Sciences of USSR, 1947.
2. Bedford, F., C. Rutland, P. Dittrich, A. Raab, and F. Wirbeleit. "Effects of Direct Water Injection on DI Diesel Engine Combustion." SAE Technical Papers 2000-01-2938, 2000.
3. Greeves, G., I. M. Khan, and G. Onion. "Effects of Water Introduction on Diesel Engine Combustion and Emissions." Symposium (International) on Combustion 16 (1): 321-336, 1977.
4. Kadota, T & Yamasaki, H. (2002). "Recent advances in the combustion of water fuel emulsion." Progress in Energy and Combustion Science 28 (5), 385-404, 2002.
5. Nour, M., H. Kosaka, A. K. Abdel-Rahman, and M. Bady. "Effect of Water Injection into Exhaust Manifold on Diesel Engine Combustion and Emissions." Energy Procedia 100 (2016) 178-187, 2016.
6. Ishida, M., H. Ueki, and D. Sakaguchi. "Prediction of NO_x Reduction Rate due to Port Water Injection in a Di Diesel Engine." SAE Technical Papers 972961, 1997.
7. Ma, X., F. Zhang, K. Han, Z. Zhu, and Y. Liu. "Effects of Intake Manifold Water Injection on Combustion and Emissions of Diesel Engine." Energy Procedia 61 (2014) 777-781, 2014.
8. Farag, M., H. Kosaka, M. Bady, and A. K. Abdel-Rahman. "Effects of Intake and Exhaust Manifold Water Injection on Combustion and Emission Characteristics of a DI Diesel Engine." Journal of Thermal Science and Technology 12 (1), 2017.
9. Subramanian KA. "A comparison of water–diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions." Energy Conversion Management (2011) 52:849-57, 2011.
10. Radloff, Ernst & Gautier, Charles. (2005). "Diesel Engine NO_x Reduction Using Charge Air Water Injection." ASME, Internal Combustion Engine Division Fall Technical Conference (ICEF2005), 11–14, pp. 55-66, 2005.
11. Sagar Patel, Gaurav P Rathod, Tushar M Patel. "Experimental investigation of diesel engine with water injection system on emission parameters." IOSR Journal of Mechanical and Civil Engineering. 2278-1684, p-ISSN: 2320-334X, Volume 11, PP 47-51, 2014.
12. Udayakumar, R., S. Sundaram, and R. Sriram. "Reduction of NO_x Emissions by Water Injection into the Inlet Manifold of a Di Diesel Engine." SAE Technical Papers 2003-01-0264, 2003.
13. S. Sandeep, D. Senthil Kumar, S. Krishnan, S. K. Pandey, "Assessment of Atomized Water Injection in the Intake Manifold of a Heavy Duty Diesel Engine for NO_x Reduction Potential" IOP Conf. Series: Materials Science and Engineering 577 (2019)
14. D Senthil Kumar, S Thirumalini and H S S K Praveen, "Experimental investigation to improve performance and emission characteristics of a diesel engine by using n-butanol as additive to the biodiesel-diesel blends" IOP Conf. Series: Materials Science and Engineering 577 (2019).

15. D. Senthil Kumar & S. Thirumalini (2020): *Investigations on effect of split and retarded injection on the performance characteristics of engines with cashew nut shell biodiesel blends*, *International Journal of Ambient Energy*. doi.org/10.1080/01430750.2020.1730961.
16. R. Vishnu Varthan and D. Senthil Kumar, "Emission Characteristics of Turbocharged Single Cylinder Diesel Engine", *Indian Journal of Science and Technology*, Vol 9(17), May 2016